



# A Review of Tribomaterial Technology for Space Nuclear Power Systems

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# **A Review of Tribomaterial Technology for Space Nuclear Power Systems**

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## **Abstract**

The National Aeronautics and Space Administration (NASA) has recently proposed a nuclear closed-cycle electric power conversion system for generation of 100-kW of electrical power for space exploration missions. A critical issue is the tribological performance of sliding components within the power conversion unit that will be exposed to neutron radiation. This paper presents a review of the main considerations that have been made in the selection of solid lubricants for similar applications in the past as well as recommendations for continuing development of the technology.

## **Introduction**

### **Review of Nuclear Technology for Space Power and Propulsion Systems**

There are three main types of nuclear power conversion technologies for space propulsion systems: nuclear thermal rocketry, nuclear thermoelectric power conversion, and nuclear closed-cycle electric power conversion (ref. 1). Although the original focus of the latter two technologies was to provide power for propulsion systems, the electrical power could be used for alternate purposes such as lunar mining and data transmission during long-duration space exploration missions. In fact, current NASA nuclear program goals are directed toward space power for the lunar surface with future missions targeting propulsion for long-duration travel. A brief description of each technology as it relates to space exploration will be given in this section.

#### ***Open-cycle nuclear thermal propulsion***

Nuclear Thermal Rocketry (NTR) relies on a fission reactor to heat a propellant for propulsion. NTR technology, as developed for the Nuclear Engine for Rocket Vehicle Applications (NERVA) program in the 1970s, would not require moving components, similar to conventional rocketry, and would be capable of much higher speed, shorter-duration space travel. However, the NERVA program was canceled in the 70s with waning interest in human space exploration and the problems associated with effluent emissions having yet to be addressed.

#### ***Nuclear thermoelectric power conversion***

Employed extensively in NASA missions from Apollo to Cassini, Nuclear Radioisotope Thermoelectric Power is driven by the release of energy produced from the decay of a radioactive element. On Cassini, for example, plutonium-238 is allowed to decay to uranium, releasing energy (heat) that is converted into electrical power by thermocouples. More recently, systems have been developed to convert the resultant electricity into propulsion force by driving a gaseous propellant between two grids under a potential difference. The level of energy produced by this method (typically ~100-W) is relatively low and would be best suited for low acceleration, long-duration space travel. However, this method is considered safe and reliable and there are no moving parts in the system.

### ***Nuclear closed-cycle electric power conversion***

With a renewed interest in nuclear power for proposed Lunar or Martian stations, and the possible need for long-distance nuclear powered space exploration vehicles, NASA is focused on the development of Nuclear-Electric Propulsion (NEP) systems. NEP uses a fast-neutron fission reactor to heat a fluid. The fluid thermal energy is converted into electrical power through a turbine-based power conversion system. This type of system is best suited for long-duration, low acceleration space exploration missions and has been proposed for previous missions. The SP-100 mission proposed the generation of 2.4 MW of thermal energy from a uranium nitride reactor cooled with liquid lithium. Of the planned 10 year mission duration, the system would have been required to operate at full power for 7 years. The control drive assembly actuators for this system were to operate from 930 to 1230 °C at  $10^{-11}$  torr. Much of the tribomaterials selection was inherited from the Space Nuclear Auxiliary Power (SNAP) Program, which had similar requirements for durability in a fast neutron field and in vacuum. However, the SNAP reactor would only have needed to operate for 10,000 hr at 630 °C (ref. 2).

The advantage of the NEP system is the generation of considerably more power (~100-kW), which would provide sufficient power for extraterrestrial mining operations or deep space data transmission (ref. 3). The disadvantages include the lack of experience with this type of system and the fact that the power conversion system requires moving parts. The moving components of the power conversion system and the impact of tribology on them are the main concerns of this review.

## **Tribological Considerations for Project Prometheus Nuclear Power and Propulsion**

### ***Reactor control mechanisms***

Within the reactor, drive mechanisms must be able to move control rods with great precision within sliding bearings. The ability to control the stroke of these elements is mission critical and highly dependent upon the coefficient of friction these members experience upon actuation of the mechanism. The static coefficient is of particular concern since the material pairs in sliding contact can be stationary for long intervals. High static friction could make control rod motion difficult to control. Therefore, candidate materials in this system must have high thermodynamic stability and little tendency for diffusion welding.

### ***Power conversion system***

A proposed reactor incorporates a liquid metal-to-gas heat exchanger with a closed-Brayton-cycle power conversion system designed to deliver 100-kWe to the science package (refs. 4 and 5). The proposed power conversion system is comprised of a recuperator, a gas cooler, and a turboalternator, incorporating the design elements of the Brayton rotating unit (BRU) and mini-BRU systems under development at NASA. The proposed working fluid is a 50 mol% mixture of helium and xenon gases. The single-shaft, radial turboalternator is to be supported on foil gas bearings (hereafter referred to as *foil bearings*).

### ***Foil bearing operating characteristics***

A typical foil bearing for journals is composed of two or more flexible concentric metal foils (fig. 1), which are fixed to the bearing housing on one end. A corrugated *bump foil* responds to radial loading to provide Coulomb damping. A smooth *top foil* helps in the generation of a hydrodynamic gas film (refs. 6 and 7), which lubricates the surfaces that are in relative motion. Hydrodynamic lubrication is characterized by friction coefficients on the order of 0.01 and almost negligible wear (ref. 8). However, during start-up and shut-down or in extreme loading conditions, the top foil comes into contact with the journal due to the absence of sufficient hydrodynamic forces. For this reason, a coating is normally applied to the journal to reduce friction and wear at the specified portions of the operation cycle.

### ***The need for a review of the effects of radiation on solid lubricants***

The effect of radiation (including x-rays, gamma rays, protons, neutrons and electrons) on structural materials and coatings has been studied extensively since the advent of the nuclear energy programs in the 1950s. However, for the majority of these applications, the same considerations for system weight and size do not have to be made. For example, land-based reactors can take advantage of heavy shielding and distancing of sensitive components from the source radiation. The same is essentially true for nuclear submarines. For spacecraft, however, where launch weight and vehicle size are critical, the same “simple” solutions are not available. Moreover, where the possibility for swelling of key system elements may lead to misalignment or seizure, in the worst case, knowledge of the specific system materials becomes mission critical. Since the response of the proposed coating materials for the power conversion unit are unknown, the issue warrants further study. These issues will be discussed later in this paper.

## **Discussion**

Advanced tribomaterials are required for extreme environments. Solid lubricants are required for lubrication of sliding surfaces, such as foil bearings, where the use of conventional petroleum-based lubrication is impractical or unfeasible. For example, most oils or greases thermally decompose at temperatures above 350 °C. The high vapor pressure of liquid lubricants typically does not allow their use in vacuum environments. Liquid lubricants cannot be used in reactive environments such as corrosive gases and liquid metals and they are typically not used in environments where radiation is present. Solid lubricants are most desirable in these applications and are often used in combination with wear resistant hard coating materials.

Damage tolerance limits for general materials classes are given in table 1. The type of damage created by radiation exposure depends on the characteristics of the radiation and on the material properties. Radiation can be electromagnetic (x-rays and gamma rays), light charged particles (electrons), heavy charged particles (protons and alpha particles) and heavy neutral particles (slow neutrons and fast neutrons). The effect of radiation exposure is a function of the radiation energy, flux (incident particles per unit of time), exposure time (total dose) and the mass and charge of the particles. For example, ionization damage due to electron radiation is negligible for most engineered materials except polymers. Damage by nuclear collisions with atoms in the irradiated material may take the form of dislocation pile-ups (refs. 9 and 10). Energy deposited by incident radiation, may cause thermal spikes or atomic displacement within irradiated materials. Finally, element transformation or fission may also result from bombardment with nuclear particles. The possible overall effects of radiation exposure on materials include increased electrical resistivity, increased elastic modulus, increased work hardening, decreased ductility, decreased impact strength and decreased ductile-to-brittle transition temperature (ref. 10). The relevance of this to solid lubrication lies in the effect radiation may have on the mechanism of lubrication, which will be discussed after a brief review of solid lubricant coatings.

### **Solid Lubricant Coatings**

Solid lubricant coatings are applied between sliding surfaces by a variety of techniques. Simple methods include rubbing the material on in loose powder form by hand (*burnishing*) or application with an aerosol-based carrier. Coatings can be applied by dipping, electroplating, diffusion or thermal spray techniques. Other more complex methods include sputtering, ion implantation or chemical and physical vapor deposition. The mechanical system configuration and the required performance characteristics determine the type of solid lubricant and its necessary deposition technique. The purpose of this section is to describe some of the basic properties of general classes of solid lubricants, grouped according to coating thickness.

### ***Thin film solid lubricants***

In this review, thin films are classified as films up to 50  $\mu\text{m}$  in thickness. Films of this thickness would primarily be considered for foil coatings in a foil bearing system, but could also be employed as *break-in* coatings on journals, which are applied to aid in the initial development of a beneficial transfer layer between the journal and compliant foil. Thin films will be discussed in two major categories, grouped by their lubrication mechanism.

***Layer-lattice materials.***—Layer-lattice (or lamellar) type solid lubricants are so named because they have atomic structures that consist of weakly bonded, alternating layers that are arranged in such a way that lubrication is enhanced by fracture along these lattice planes when a shear force is applied. Materials with high ratios of atomic plane spacing with respect to interatomic spacing within a plane tend to possess this characteristic. Examples include graphite, hexagonal boron nitride (HBN), dichalcogenides (including disulfides, diselenides and ditellurides of transition metals such as molybdenum, tungsten, niobium and tantalum) and monochalcogenides (such as gallium selenide and tin selenide) (refs. 8, 11, and 12).

In graphite, weak pi-bonds bind adjacent crystallographic planes of strongly-bound hexagonally arranged carbon atoms. The orientation of these bonds is shown schematically in figure 2 (ref. 13). Figure 2(a) shows the most common ABABAB... stacking order with the resulting unit cell on the right. A small percentage of naturally occurring graphite will also have the ABCABCABC... stacking order shown in figure 2(b). In both cases, the pi-bonds are easily broken in shear due to the presence of adsorbed water vapor, which provides lubrication between the sliding crystal planes. Graphite retains this lubricating capability up to approximately 550 °C, above which vapor desorption and oxidation occur. The use of graphite in vacuum (less than  $10^{-6}$  torr) and at temperatures greater than 550 °C has been explored by trapping impurities in the material lattice (ref. 14).

Similarly, molybdenum disulfide has relatively weak van der Waals bonds between adjacent atomic planes of sulfur (shown schematically in figure 3), which gives this material its lubricating properties. Unlike graphite, friction coefficients for this material tend to be lower in vacuum because adsorbed gas molecules act to slightly increase friction (ref. 15). Dichalcogenides such as  $\text{MoS}_2$  tend to oxidize at temperatures above 400 to 500 °C, losing lubricious properties (refs. 14 and 16). These materials have been used extensively in nuclear reactors, which will be discussed in a later section.

***Non layer-lattice materials.***—Non-layer-lattice solid lubricants provide lubrication by plastic deformation of the material. Elevated temperatures may enable deformation. In general, this classification of solid lubricants includes polymers, soft metals, metal salts and oxides.

Polymers such as polyimide, polyethylene (PE), nylon, and polytetrafluoroethylene (PTFE) have been used as solid lubricants due to their good thermal stability, wear resistance, effectiveness in vacuum and with exposure to nuclear radiation (ref. 17). Fillers such as graphite,  $\text{MoS}_2$  and  $\text{CF}_x$ , and reinforcements such as carbon fiber may be used to improve performance characteristics of the polymer films, but typically reduce physical properties such as load carrying capability (ref. 11). Fusaro and Sliney (ref. 18) showed that polyimide, and polyimide with  $\text{MoS}_2$  or  $\text{CF}_x$  filler provided lubrication in standard laboratory bench tests up to approximately 500 °C in air. These films were also tested as break-in coatings on foil gas bearings and were found to be effective up to 350 °C (ref. 19).

Soft metal films such as Ag, Au, Ba, Bi, Cu, Pb, Sn, Tl, and Zn are typically used in high temperature applications where little sliding contact occurs (such as rolling-element bearing systems). This category of solid lubricant also includes fluorides of alkali, alkaline earth and rare earth metals as well as some lubricious oxides such as  $\text{PbO}$ ,  $\text{MoO}_3$ ,  $\text{K}_2\text{MoO}_4$ ,  $\text{Co}_2\text{O}_3$ , and  $\text{NiMoO}_4$  (refs. 12 to 15). Alkaline earth fluorides such as  $\text{CaF}_2$ ,  $\text{LiF}$  and  $\text{BaF}_2$ - $\text{CaF}_2$  are effective solid lubricants from approximately 400 to 800 °C. Lanthanide trifluorides such as  $\text{LaF}_3$  and  $\text{CeF}_3$  were also found to be useful from 540 to 1000 °C. A major advantage of the fluorides is their high thermo-chemical stability. This makes these materials attractive for use in reactive environments and near nuclear reactors, for which their study was initiated. For the oxides, thermo-chemical stability is not always assured. Table 2 lists the free energy of formation at 1000 K for several fluorides and oxides. The more negative the free energy of formation, the greater its



chemical stability, reducing the compound's tendency for oxidation. PbO is combined with SiO<sub>2</sub> to form a silicate phase that protects PbO from oxidation to Pb<sub>3</sub>O<sub>4</sub> from 350 to 500 °C in air. However, below 250 °C, friction and wear are high. This kind of information can be used to engineer coating systems. For example, the problem could be mitigated by the combination of two solid lubricants, one for low temperature lubrication and one for high temperatures. An excellent discussion of these and other more exotic solid lubricants was published by Bisson (ref. 12).

### ***Thick film solid lubricants***

For the purpose of this review, thick films will be classified as films greater than 50 µm in thickness. Coatings of this type are applied to the journal and will be discussed in terms of their deposition techniques.

***Fused coatings.***—To form a fused coating, a liquid-based suspension or slurry containing the solid lubricant is prepared. The mixture is then applied to the surface of the article by spraying or dipping. The article is then heated to the melting point of the solid lubricant to form the coating. Preliminary testing of fused coatings showed that, though the solid lubricants provided low friction, coating durability was very low and seemed to depend on variation in the deposited coatings (ref. 20). Since then, considerable work has been done to control deposition thicknesses and final coating compositions. However, high wear is still a significant issue since the coating cannot be replenished. For long-duration operation like the proposed Prometheus mission, coatings with both low friction and high wear resistance are required. A solution is offered through composite coatings that combine low friction from incorporation of solid lubricants and wear resistance from hard phases. These materials can be deposited consistently by thermal spray techniques.

***Thermal spray coatings.***—The NASA PS100, PS200, and PS300 families of solid lubricant-based materials are fluoride-based coatings for high temperature applications (ref. 8). The PS304 coating system (ref. 21) was developed for improved finishing and performance characteristics compared to the previous generations (ref. 22). The composition of this coating is 60 wt% nichrome (80Ni-20Cr), 20 wt% chromia (Cr<sub>2</sub>O<sub>3</sub>), 10 wt% silver and 10 wt% binary eutectic barium fluoride - calcium fluoride (68BaF<sub>2</sub>-32CaF<sub>2</sub>). Nichrome is a binder that, along with chromia, provides wear resistance. Silver and BaF<sub>2</sub>-CaF<sub>2</sub> are solid lubricants at low and high temperatures, respectively. The fluorides begin to soften and lubricate above 400 °C (ref. 23). The coating is deposited on the sliding surfaces of the bearing by thermal spray processing.

Thermal spray processes include combustion (flame spray, detonation gun and high-velocity oxy-fuel), plasma flame and electric arc processes (refs. 24 to 26). Since PS304 is a multi-component coating system, the feedstock is prepared as a powder blend composed of each of the constituents and deposited by plasma spray or high-velocity oxy-fuel (HVOF) processes. In the plasma spray process, particles of the deposition material are injected into a plasma flame, which is produced by the ionization of an inert gas. Alternatively, the HVOF system burns an oxygen-fuel mixture inside a combustion chamber where the feedstock is introduced. In both systems, the flame heats the particles to a molten or semi-molten state. The particles then strike the substrate and quickly solidify forming the coating layer.

### **Coating Properties Determination**

Standardized test methods have been developed for evaluation of the integrity and performance characteristics of various types of coatings. The initial tribological properties of a coating depend greatly on the surface roughness. The coating roughness determines the contact area of the opposing surfaces and influences the development of the beneficial transfer layer. The two general methods of surface roughness measurement techniques that are available are stylus and optical profilometry (ref. 8). Stylus profilometers employ a cantilever mechanism that translates a stylus over the specimen. Optical profilometers process light reflected from multiple points on a surface of interest through a comparator to

generate the required measurements. The undulations on the surface are recorded with standard metrics such as root-mean-squared peak-to-valley height.

Friction and wear of material pairs can be evaluated with a variety of test methods. Figure 4 shows several of these methods schematically. One of the most widely used friction and wear test configurations is pin-on-disk (fig. 4(a)). A schematic of the high temperature pin-on-disk apparatus at Glenn Research Center is shown in figure 5. During the test, a cylindrical pin is loaded against a coated rotating disk. The friction coefficient is calculated by dividing measured tangential force acting on the pin by the applied normal load. As the test runs, a groove is typically worn into the coated surface as material is also worn from the end of the pin. A calculation of the volume of material worn is used to compare the performance of material pairs at various test conditions (ref. 8).

Separate techniques are often employed between thin films and thick films to determine their hardness and adhesive strength due to their different physical characteristics. The remainder of this section discusses test methods for the two general categories of coatings separately.

### ***Thin film test methods***

The wear of a coating is strongly dependent upon the coating hardness, which can be assessed through indentation methods. Thin coatings generally employ microindentation hardness techniques. In this type of test, a standard pyramidal stylus is impressed upon a flat specimen with a selected normal load (ref. 27). The size of the impression is used to calculate the hardness of the material, where hardness is inversely proportional to indentation size.

Adhesion can be assessed with the so-called tape test (ref. 28). In this test, a coated specimen is scored and adhesive tape is affixed over the scored area. The tape is removed and the amount of removed coating is quantified. Another adhesion test is known as the bend test (ref. 29), in which a coated specimen is successively bent 180 °C over a fixture. Any delamination of the coating would be likely to occur at the bends. Adhesion characteristics can also be examined with the scratch test, where a diamond stylus is dragged across the coated surface of a specimen (ref. 8). The nature and width of the resulting scratch channel are used to compare coating adhesion and hardness. The normal load on the stylus is predetermined and the coefficient of friction can be calculated as the ratio of the tangential force to the normal load.

### ***Thick film test methods***

The hardness of thick coatings can also be assessed by microindentation hardness measurement techniques mentioned previously. In addition, for coatings that have phases with relatively large differences in physical properties (such as composite coatings with intermingled hard and soft phases) macro hardness tests can be used (ref. 30).

Adhesion is measured by standard test methods (refs. 31 and 32) where an adhesive is used to affix the top surface of the coating to the test apparatus. A force is applied normal to the coated surface until failure occurs, either at the coating-substrate interface (adhesive failure), within the coating (cohesive failure), at the adhesive-coating interface or a combination of these modes.

## **Properties of Irradiated Solid Lubricants**

### ***Dimensional stability***

Very little data exists on the dimensional stability of solid lubricants during neutron exposure. One study showed that the lattice expansion of a LiF crystal after exposure to a fast neutron fluence of approximately  $10^{16}$  neutrons/cm<sup>2</sup> was a mere 0.12 percent (ref. 33). The lattice expansion was likely due to the generation of Frenkel defects, by which a displaced atom moves to an interstitial position and leaves behind a vacancy. A similarly mild effect might be expected for other fluoride solid lubricants after neutron exposure.

### ***Diffusion welding***

Selection of tribomaterials for previous space power reactors has been reported previously (refs. 2, 34 to 37). Over 120 material pairs in groups composed of general material categories were tested in the 1960s for the SNAP Program. Carbon-graphite against  $\text{Al}_2\text{O}_3$ -coated metals was resistant to friction and wear above 500 °C in vacuum (ref. 2). In addition,  $\text{Al}_2\text{O}_3$  against  $\text{MoS}_2$  in a sodium silicate binder or graphite gave friction coefficients less than 0.2 from room temperature to 550 °C in vacuum. In subsequent investigations, graphite and alumina were selected for sliding bearings in Ar and cermets containing ZrC, HfN, and HfC were selected for bearings in liquid Li (refs. 34 and 35). These materials were selected based on their predicted thermochemical stability to reduce the possibility of diffusion welding. Unfortunately, the program was terminated before the evaluations were complete. The evaluation of static friction characteristics of these tribomaterials was not part of these preliminary investigations.

Ring et al. reported on attempts to develop bearing coatings to prevent self-welding and galling wear of sliding component surfaces in space power reactors (ref. 36). The system components were required to operate maintenance-free for 10 years in ultra-high vacuum at approximately 930 to 1230 °C with neutron fluences up to  $10^{22}$  n/cm<sup>2</sup>. They based coating material selection on high thermodynamic stability, high melting temperature and compatibility with the Nb-1Zr substrate (e.g., similar thermal expansion coefficient). All but carbide ceramics were eliminated from consideration due to predicted incompatibilities with the substrate. HfC and ZrC performed acceptably in static high temperature thermochemical stability tests where the coated substrate was held at 1230 °C for 300-h and examined for adverse reactions. In the same evaluation, HfC/HfC couples did not diffusion bond. ZrC did not diffusion bond to Mo or to Re, but HfC did bond to Re. The study concluded that a HfC or ZrC coating on Nb-1Zr versus Mo, Re or Mo-Re counterfaces would make acceptable materials pairs in the high temperature, high fluence environment.

Schuster (ref. 37) studied the use of  $\text{MoS}_2$  for control rods in the SP-100 reactor environment ( $2 \times 10^{15}$  n/cm<sup>2</sup>,  $E > 0.1$  MeV,  $10^{-11}$  torr). His study concluded that there was evidence of diffusion welding during static friction coefficient evaluations at  $10^{-8}$  torr and approximately 630 °C, but not at approximately 475 °C. However, the hold times were less than 20 hr and for longer time intervals, more diffusion is likely to take place. There was a reaction between the  $\text{MoS}_2$  and the Ni- and Co-based superalloy substrates in the control drive assembly, making this material unfavorable for use in that system at elevated temperatures ( $> 475$  °C). To reduce the reaction between  $\text{MoS}_2$  and the substrate, Schuster suggests the use of a TiN or  $\text{Cr}_2\text{O}_3$  bond coating, but that more research would be necessary to evaluate this technique. For example, the difference in coefficients of thermal expansion between the substrate, the proposed bond coating and the top coating could lead to delamination of the coating. There was no direct analysis of the coating for damage due to radiation exposure.

### ***Tribological properties***

McConnell, Clow, and Lavik studied the effects of radiation on the tribological properties of molybdenum disulfide, graphite, lead oxide and combinations of these materials with various binders (ref. 38). Tests were performed during radiation exposure (*dynamic irradiation testing*). The exposure consisted of  $10^9$  to  $10^{12}$  ergs/g-C gamma radiation. Tests were performed with flat-on-cylinder and sphere-on-sphere tribometers. Tests were also performed after exposure (*post-irradiation testing*) to a neutron flux of  $10^{14}$  to  $10^{16}$  nvt. The authors reported no significant influence on tribological properties from either exposure. It is important to note that there was a large amount of scatter in the reported data, probably due to the difficulty associated with applying a coating consistently.

A study by McDaniel compared the tribological properties of lead sulfide and molybdenum disulfide in a boric oxide binder, molybdenum disulfide and graphite in a sodium silicate binder and calcium fluoride with an oxide frit before and after gamma ( $10^{11}$  erg/g-C) and neutron ( $10^{16}$  neutrons/cm<sup>2</sup>) irradiation (ref. 39). The tests were performed with a flat-on-cylinder tribometer from room temperature to 815 °C. No significant effect was observed with respect to radiation exposure. The same result was

reported for these coating systems by other investigators up to 650 °C. However, large scatter in the data was again likely due to inconsistent coating application as noted previously.

Essentially no effect was observed from radiation exposure when Lewis and McDaniel performed post-irradiation friction and wear tests of molybdenum disulfide or graphite in various binders (ref. 40). The tests were performed after exposure to fast neutrons at a fluence of  $10^{14}$  to  $10^{16}$  n/cm<sup>2</sup> at temperatures from room temperature to 650 °C in air and under vacuum.

Fedorchenko et al. (ref. 41) studied the frictional properties of sintered Fe-based materials with CaF<sub>2</sub> additions with respect to heat treatment (160 h at 630 °C) and fast neutron exposure ( $0.56 \times 10^{20}$  n/cm<sup>2</sup>) for use in sodium-cooled nuclear plants. Ti-stabilized Fe-18Cr-10Ni (18–10 steel) was slid against alloyed Fe-15Mo with 6 wt% CaF<sub>2</sub> added to the powder metallurgy charge. Heat treatment caused precipitate formation, which increased the hardness and wear resistance in tribometer experiments in an Ar/liquid Na atmosphere. Irradiated specimens had essentially the same wear as the control case but the coefficient of friction increased from 0.13 to 0.31. In comparison, the friction coefficient for the heat treated (non-irradiated) case was 0.33. This study indicates that this composite tribomaterial had no change in wear characteristics due to static neutron exposure and had essentially the same friction characteristics as specimens exposed to a moderate heat treatment.

A study that reports an effect due to radiation exposure of solid lubricant coatings was published by Jacobson (ref. 42). In his investigation, the tribological properties of molybdenum disulfide and graphite in a sodium silicate binder were evaluated via pin-on-disk testing. A special test apparatus was designed and constructed to allow testing in a reactor pile (ref. 43). The neutron fluence was  $10^{15}$  to  $10^{18}$  n/cm<sup>2</sup>. The test was run at 10 and 13.3 m/s with a 1-kg load at 150 °C in dry air. This study showed that the friction coefficient and wear increased with increasing neutron flux (in dynamic irradiation testing) rather than with respect to increasing neutron fluence (in post-irradiation testing). The results of the Jacobson study are significant because they show a distinct difference in the tribology during and after irradiation. Jacobson hypothesized that the difference in post-irradiation and dynamic irradiation tests may be due to the combination of damage that takes place from irradiation and wear processes during dynamic studies, which does not exist in post-irradiation studies.

### **High-Temperature Tribology in Helium-Xenon**

In addition to maintaining acceptable performance during radiation exposure, solid lubricants for the current investigation must have predictable performance in the inert He-Xe working fluid that has been proposed for the Prometheus power conversion system. However, Xe is a very expensive material and no known studies of tribology in this gas exist. Due to the fact that a 50 mol% mixture of He and Xe is proposed for the current application, and since the atomic mass of Xe is more than 30 times that of He, it would be reasonable to compare results of tribological evaluations in He as a screening tool for characterizations in He-Xe.

Studies have been underway for a number of years within NASA (ref. 44) and more recently overseas with groups such as Japan Atomic Energy Research Institute (JAERI), the Commissariat à l'Énergie Atomique (CEA) in France and the Institute of Nuclear Energy Technology in Beijing that are interested in materials pairs for use in high temperature gas-cooled reactors. The primary need is for control rod bearings that operate at high temperatures and high neutron fluence levels and are required to make slight movements after long periods of quiescence. As mentioned previously, a primary concern is diffusion welding of the material pairs. Solid lubricants are paired with ceramic coatings in this situation, due to the high temperature thermochemical stability of ceramics. Examples include carbides and/or oxides of Cr, Zr, and Hf. In a study by Cachon et al. (ref. 45), the static coefficient of friction ranged from 0.4 to 0.7 for an unspecified homogeneous material sliding against a metal alloy, yttria-stabilized ZrO<sub>2</sub> or a PVD-deposited amorphous carbon material up to 1,000 °C.

## Summary

Nuclear systems for space power have been under consideration for a number of years. A recent proposal called for the development of a nuclear closed-cycle electric power conversion system for generation of 100-kW of electrical power that will have various tribological issues. Key components in the system will experience sliding contact at elevated temperatures while being exposed to neutron irradiation. The purpose of this review is to identify the relevant issues for tribological materials in space nuclear power systems based on past attempts to develop this technology. Of the solid lubricants, graphite and molybdenum disulfide represent general classes of coating materials that have been reported by several groups to be resistant to gamma and neutron irradiation after static exposures. The work of Jacobson, however, indicates that the combined effects of radiation damage and surface deformation during wear processes must be considered to get a realistic assessment of the performance of these materials near a nuclear reactor. Polymers such as polyimide are also reported to have good tribological properties and good radiation resistance. Due to the high thermochemical stability of the metal fluorides, and improvements in the understanding of microstructure-property relationships for coatings containing metal fluorides, this coating should also be considered for use in the proposed application.

Preliminary studies should be performed to determine the dimensional stability, adhesion strength and resistance to diffusion welding of the candidate coating materials after exposure to reactor radiation. Additionally, evaluation of the tribological performance of the candidate coating materials during radiation exposure is necessary.

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TABLE 1.—DAMAGE TOLERANCE LIMITS OF MATERIALS (REF. 42)

Material class	Gamma dose, rad (carbon)	Neutron fluence, n/cm <sup>2</sup> (E≥1 MeV)
Elastomers	10 <sup>7</sup>	10 <sup>15</sup>
Organic fluids	10 <sup>8</sup>	10 <sup>16</sup>
Plastics	10 <sup>9</sup>	10 <sup>17</sup>
Ceramics	10 <sup>8</sup> -10 <sup>11</sup>	10 <sup>17</sup> to 10 <sup>20</sup>
Metals	10 <sup>9</sup> -10 <sup>13</sup>	10 <sup>18</sup> to 10 <sup>22</sup>

TABLE 2.—FREE ENERGY OF FORMATION FOR SELECTED SOLID LUBRICANTS

Material	Free energy of formation at 1000 K (kcal/gram-atom of oxygen)
PbO	–30
MoO <sub>3</sub>	–40
Cr <sub>2</sub> O <sub>3</sub>	–69
CeF <sub>3</sub>	–120
LaF <sub>3</sub>	–121
LiF	–122
BaF <sub>2</sub>	–123
CaF <sub>2</sub>	–125

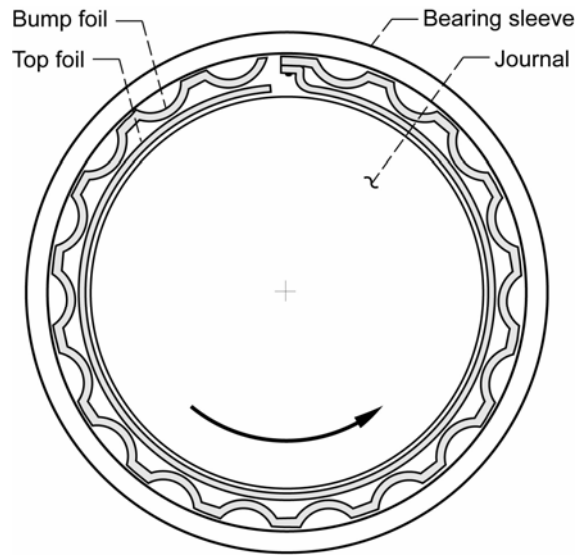


Figure 1.—Cross-sectional diagram of a foil bearing.

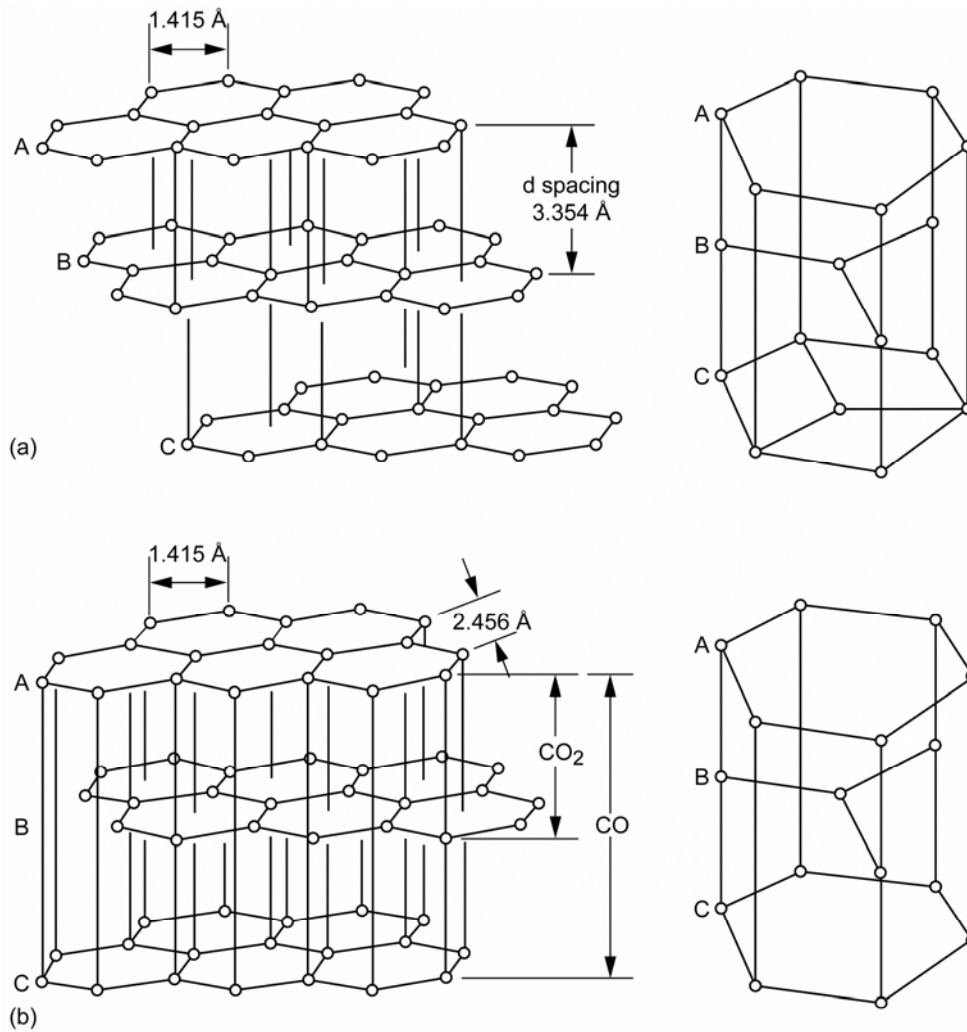


Figure 2.—Crystal structure of graphite.



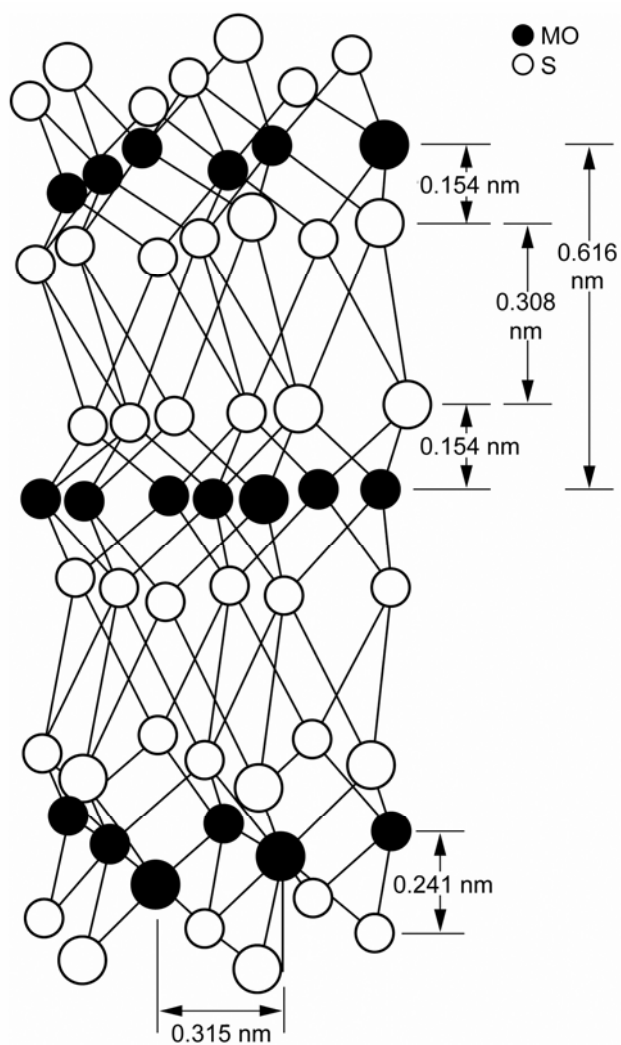


Figure 3.—Crystal structure of molybdenum disulfide.

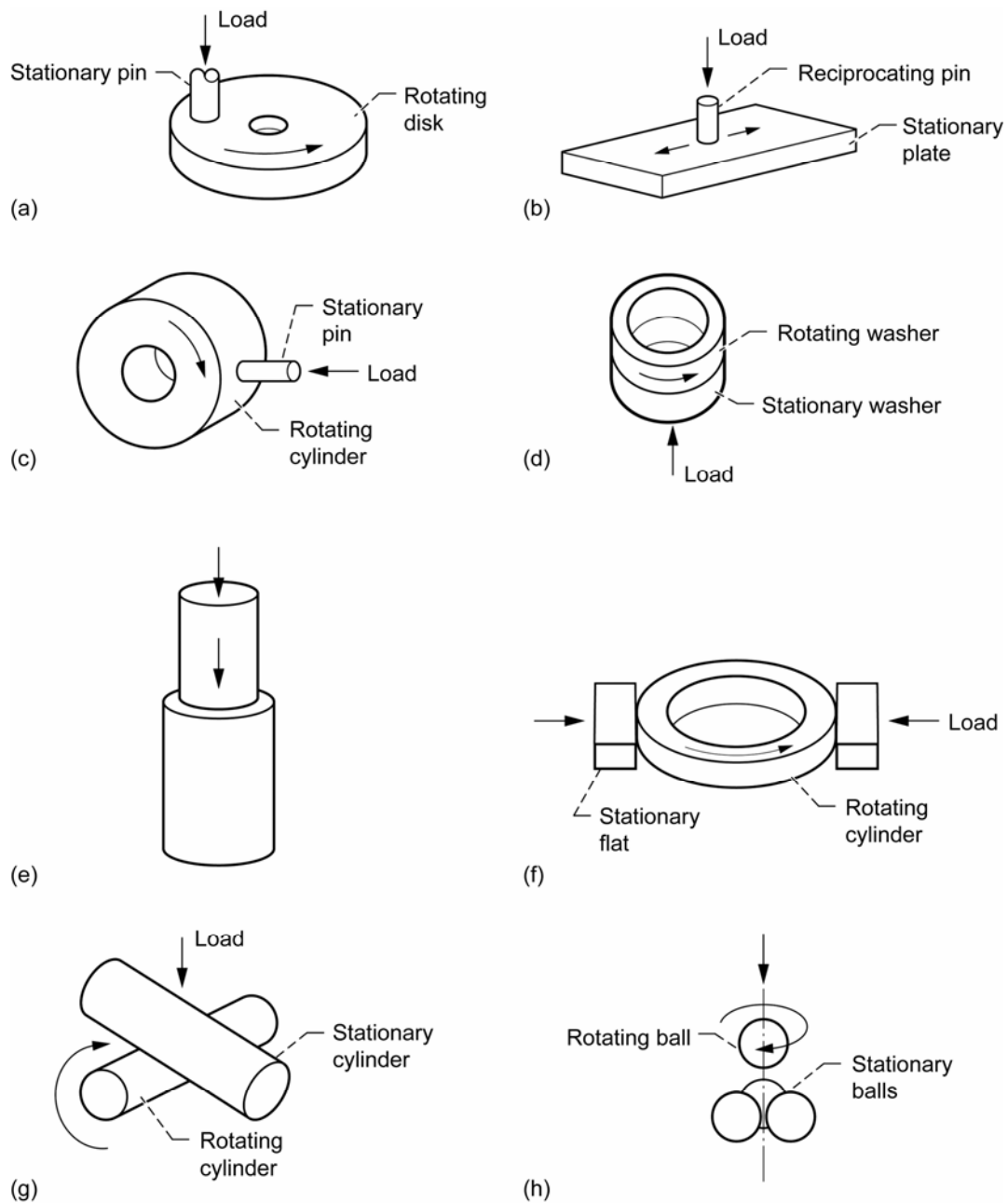


Figure 4.—Tribological tests.

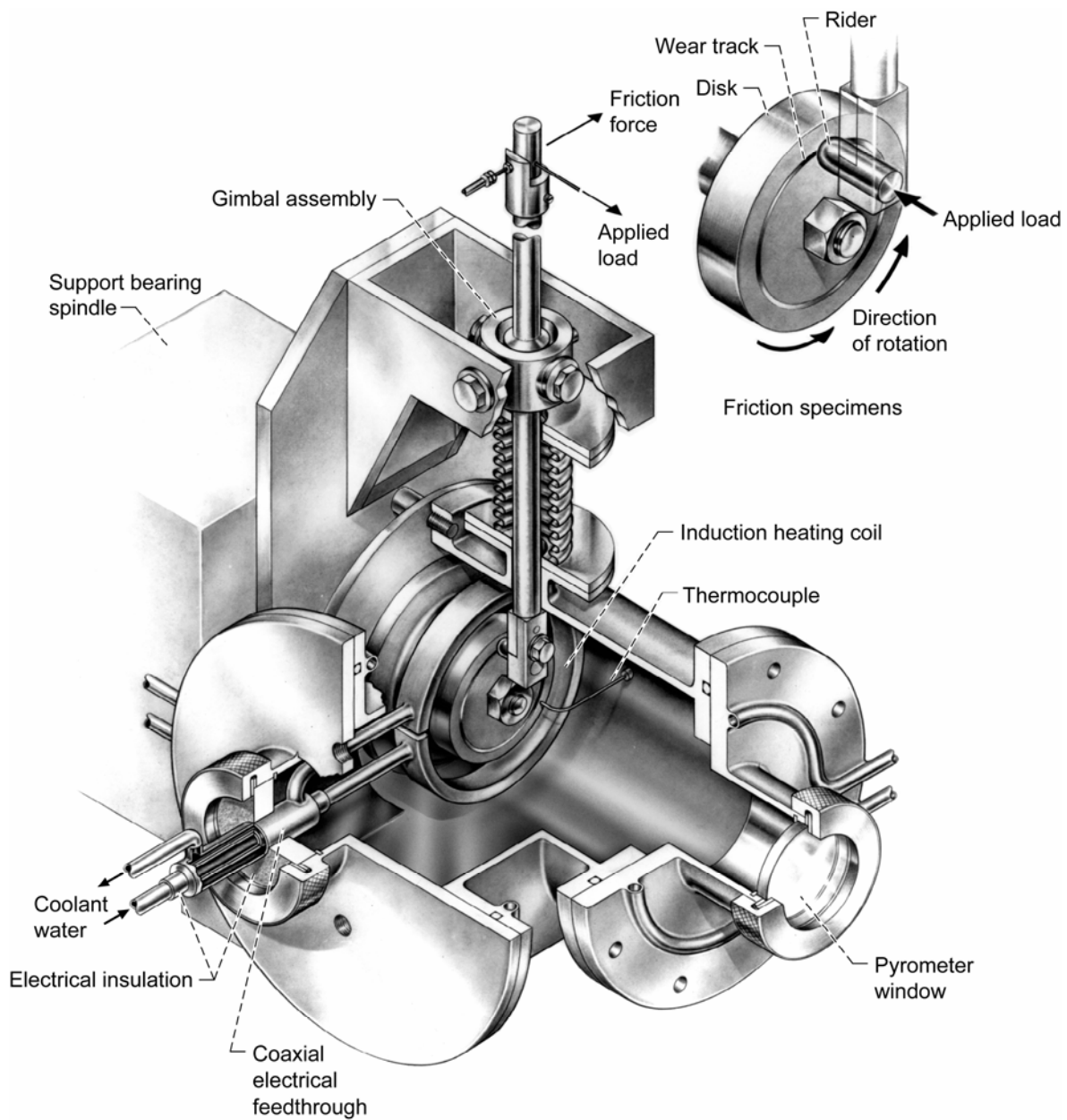


Figure 5.—High temperature tribometer.

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14. ABSTRACT The National Aeronautics and Space Administration (NASA) has recently proposed a nuclear closed-cycle electric power conversion system for generation of 100-kW of electrical power for space exploration missions. A critical issue is the tribological performance of sliding components within the power conversion unit that will be exposed to neutron radiation. This paper presents a review of the main considerations that have been made in the selection of solid lubricants for similar applications in the past as well as a recommendations for continuing development of the technology.					
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